FULL-SCALE WIND TUNNEL TEST OF AN INDIVIDUAL BLADE CONTROL SYSTEM FOR A UH-60 HELICOPTER

Stephen A. Jacklin, Aerospace Engineer
NASA Ames Research Center, Moffett Field, CA
sjacklin@mail.arc.nasa.gov

Axel Haber, Deputy Director of Research and Development
ZF Luftfahrttechnik GmbH, Kassel-Calden, Germany
axel.haber@zf.com

Gary de Simone, Manager of Advanced Technology
Sikorsky Aircraft Corporation, Stratford, CT
gdesimone@sikorsky.com

Thomas R. Norman and Cahit Kitaplioglu
NASA Ames Research Center, Moffett Field, CA
tnorman and ckitaplioglu@mail.arc.nasa.gov

Patrick Shinoda
US Army AeroflightDynamics Directorate (AMCOM), Moffett Field, CA
pshinoda@mail.arc.nasa.gov

Abstract

A full-scale wind tunnel test program was begun to explore the potential of an individual blade control (IBC) system to reduce noise and vibration, and to improve rotor performance of a UH-60 (Black Hawk) helicopter. The first phase of this testing was performed using the U.S. Army/NASA Large Rotor Test Apparatus (LRTA) to operate a full-scale UH-60A rotor in the NASA Ames Research Center 80- by 120-Foot Wind Tunnel. The acquired wind tunnel data set includes measurements of rotor performance, steady and dynamic hub forces and moments, rotor loads, control system loads, and blade vortex interaction (BVI) noise. The LRTA rotor balance was used to assess the level of hub vibration. Both fixed-position and traversing microphones were used to measure the BVI noise. The IBC motions were produced by hydraulic actuators that replaced the normally rigid pitch links of the UH-60 helicopter control system. The actuators were designed by ZF Luftfahrttechnik GmbH to impart up to ±6.0° blade pitch input at the 2/rev frequency and up to ±1.6° at the 7/rev frequency. In this first phase of the test, the IBC system was not tested to its full authority due to limited test time. Nevertheless, the preliminary wind tunnel data obtained demonstrated overall vibration reductions of 70% using approximately 1.0° of 3/rev IBC, and BVI noise reductions of up to 12 dB (75%) using 3.0° of 2/rev IBC.

Notation

AFDD	US Army AeroflightDynamics Directorate
BVI	Blade Vortex Interaction (noise)
BL-SPL	Band Limited-Sound Pressure Level
HHC	Higher Harmonic Control
IBC	Individual Blade Control
LRTA	Large Rotor Test Apparatus
ZFL	ZF Luftfahrttechnik GmbH

Presented at the American Helicopter Society 58th Annual Forum, Montréal, Canada, June 11-13, 2002.

Introduction

This paper reports the first, full-scale, wind tunnel test of an Individual Blade Control (IBC) system designed for a Sikorsky UH-60 (Black Hawk) helicopter. This test program was conducted under the authority of an International NASA Space Act Agreement. The partners were NASA Ames Research Center, ZF Luftfahrttechnik GmbH (ZFL), Sikorsky Aircraft Corporation, and the US Army AeroflightDynamics Directorate (AFDD). Under this arrangement, ZFL designed and fabricated the IBC system for a Sikorsky UH-60 rotor tested on the Army/NASA LRTA test stand in the Ames wind tunnels.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**
4. TITLE AND SUBTITLE **Full-Scale Tunnel Test of an Individual Blade Control System for a UH-60 Helicopter**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army Aviation and Missile Command,Army/NASA Rotorcraft Division,Army Aeroflightdynamics Directorate (AMRDEC),Moffett Field,CA,94035**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

The overall objective of the IBC research program is to assess the degree to which IBC can be used to reduce vibration and noise without incurring any net loss of rotor performance. A previous test of an IBC system designed for a BO-105 rotor and tested in the Ames 40- by 80-Foot Wind Tunnel showed that IBC greatly diminished both BVI noise and vibration. Encouraged by this finding, an IBC flight test program of the IBC technology was proposed for the Sikorsky UH-60 (Black Hawk) helicopter.

As a step towards reducing the risk of the flight test program, the partners decided to first conduct a series of wind tunnel tests using a prototype UH–60 IBC system. The wind tunnel data would help determine the size of the IBC actuators needed to reduce noise and vibration and to improve performance in actual flight testing. The objective of the first test, conducted in the Ames 80- by 120-Foot Wind Tunnel, was to test the integration of the IBC system with the Army/NASA LRTA test stand and to verify the functionality of the IBC system. If functional, it was hoped to acquire some preliminary data to assess the effect of IBC on low-speed noise and vibration. A second wind tunnel test in Ames 40- by 80-Foot Wind Tunnel is planned to evaluate the ability of IBC to control noise and vibration at all airspeeds and to improve rotor performance.

The first wind tunnel test of the IBC system in the NASA Ames 80- by 120-Foot Wind Tunnel was successfully completed in September 2001. The IBC system functionality was established and some limited IBC data were acquired. For this test, instrumented, standard UH-60A rotor blades were mounted on the Army/NASA Large Rotor Test Apparatus (LRTA) as shown in Fig. 1. The rotor was operated without the hub bifilar weights installed. This wind tunnel test was also the first test using the LRTA. The LRTA incorporates a balance to measure both the steady and dynamic (time history) loads produced by the rotor system. A complete description of the LRTA, wind tunnel installation, and UH-60 rotor hardware is provided in Ref. 1.

Fig. 1. Large Rotor Test Apparatus and UH-60A rotor installed in 80- by 120-Foot Wind Tunnel.

Background

The concept of using high-frequency blade pitch control inputs to reduce helicopter vibration has been extensively studied over the last three decades. Most of the work in this area has centered on active control schemes using actuators in the fixed system. The most prevalent of these methods, the higher harmonic control (HHC) method, has shown through analysis and testing that HHC can be used effectively to reduce helicopter vibration [Refs. 2-7]. More recently, it has also been shown that HHC can be used to achieve moderate reductions in helicopter blade-vortex interaction (BVI) noise [Refs. 8-10]. A difficulty, however, has been that the HHC inputs needed to reduce BVI noise have been found to increase vibration. The converse is also true.

Individual blade control offers the potential to find inputs that simultaneously reduce noise and vibration, while also improving rotor performance at the same time. The IBC concept utilizes actuators placed in the rotating frame, one per blade, to obtain more control degrees-of-freedom compared to HHC (for rotors having four or more blades).

In 1990 and 1991, a flight test of an IBC system was conducted on a BO-105 helicopter [Refs. 11-12]. The IBC system, designed by ZFL, replaced the rigid pitch links of the rotor with hydraulic actuators. The tests indicated that vibration reduction was possible. However, because the input amplitude was restricted for safety reasons to ±0.16° in 1990 and to ±0.42° in 1991, the potential for vibration reduction was not fully evaluated.

In order to safely evaluate the effect of larger amplitude IBC inputs, two full-scale wind tunnel tests were conducted in the NASA Ames 40- by 80-Foot Wind Tunnel using a more powerful IBC system and a BO-105 rotor on the Army/NASA Rotor Test Apparatus. This test program was an international collaborative effort between NASA, the U.S. Army AFDD, ZFL, Eurocopter Deutschland, and the DLR Institute of Flight Mechanics. The description of the IBC system, the test effort, and

the data acquired are provided in Refs. 13-15 and 18. These tests demonstrated that helicopter noise and vibration can be simultaneously reduced by up to 85% using 2/rev IBC in combination with other IBC harmonics. In addition, 2/rev IBC was shown to improve rotor performance by up to 7% at high-speed flight conditions.

Encouraged by this success, Sikorsky Aircraft, ZFL, NASA Ames, and the US Army initiated a follow-on program to demonstrate the IBC technology in flight on a Sikorsky UH-60 helicopter. As a step towards flight test risk reduction, the partners decided to test the UH-60 IBC system in the 80- by 120-Foot and the 40- by 80-Foot Wind Tunnels at the NASA Ames Research Center. The objective of the 80- by 120-Foot Wind Tunnel test was to verify the operation of the IBC system and, if possible, acquire preliminary data to assess the effect of IBC on low-speed noise and vibration. That test effort was completed in September of 2001. The objective of the follow-on test in the 40- by 80-Foot Wind Tunnel is to assess the effect of closed-loop IBC on vibration, noise, and high-speed rotor performance using both standard and wide-chord UH-60 rotor blade sets. That phase of the testing is planned for the fall of 2002.

This paper reports the findings of the IBC test conducted in the 80- by 120-Foot Wind Tunnel. This was also the first test utilizing the LRTA. The baseline testing of this new test stand (without IBC) and the efforts made to integrate the IBC system into the LRTA consumed the majority of the test time. Nevertheless, the IBC system was made operational and some preliminary data were acquired to assess the impact of open-loop IBC on noise and vibration.

IBC System

The IBC system developed for the UH-60 replaces the normally rigid blade pitch links of the rotor with hydraulic actuators. These actuators allow the pitch of each rotor blade to be changed independently of each other. These actuators were designed with the capability to impart up to ±6.0° at the 2/rev frequency and up to ±1.6° at the 7/rev frequency. This large control power was desired to quantify the benefit of large amplitude IBC inputs in the wind tunnel. Reference 16 provides a full discussion of the IBC servo-mechanism, the actuator characteristics, the automatic emergency shutdown feature, the development program, qualification testing, and installation into the LRTA. Figure 2 shows a schematic of one IBC actuator, while Fig. 3 shows an actuator as installed on the rotor.

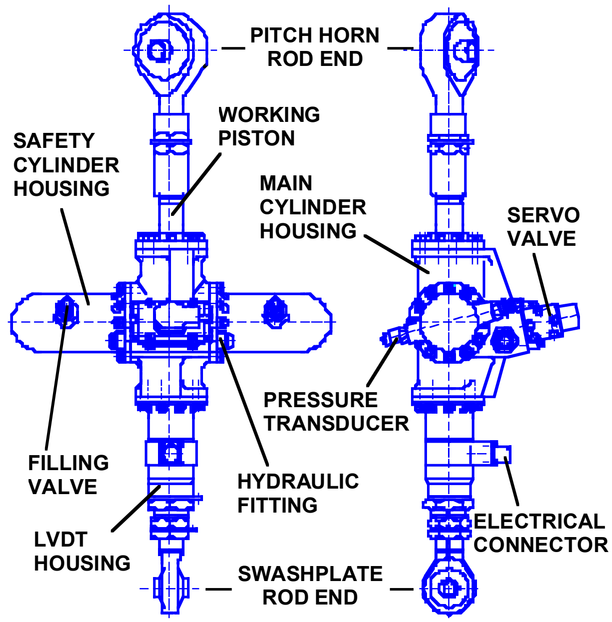

Fig. 2. IBC actuator schematic.

Fig. 3. IBC actuator installed in the rotor system.

Instrumentation and Measurements

The LRTA and UH-60A rotor were highly instrumented for safety monitoring as well as to obtain IBC research data. All data (except the data from the microphones and on-blade pressure sensors) were acquired by the wind tunnel data acquisition system at the rate of 256 samples per rotor revolution. Mean values were computed using 32 revolutions of data. The following sections summarize the primary measurements used for IBC research purposes.

LRTA Rotor Balance

The LRTA rotor balance measurements were used to compute the forces and moments generated by the rotor at the hub. A complete description of the rotor balance capability and calibration is presented in Ref. 1. The mean values used to trim the rotor (lift force, propulsive force, side force, pitch moment, and roll moment) were computed from 32 revolutions of data. The rotor balance time history records and the Fourier coefficients up to the 20th harmonic are stored in the data base. Although the mean balance data were corrected using static calibration data, a dynamic calibration was not performed to correct the Fourier coefficient data.

Microphones

Acoustic measurements were acquired from both moving and fixed microphones. The microphone traverse was equipped with eight microphones and moved under the advancing side of the rotor in the area shown in Fig. 4. This figure also shows the locations of eight other fixed-position microphones whose locations are specified in Table 1. The microphone data were recorded at a rate of 2048 samples per rotor revolution. The BVI noise component was extracted by digitally band-pass filtering the data between the 40th and 200th rotor harmonics (10th - 50th blade passage frequencies) on a post processing basis.

Blade and Control System Loads

The flap, lead-lag, and torsional blade bending loads were measured by strain gages placed at the locations shown in Table 2. The IBC actuators were instrumented with strain gages to measure the axial force developed in each actuator. These measurements were the equivalent of pitch link load forces. The bending moments on the rotating scissors and the loads on the stationary swash plate control rods were measured for safety monitoring purposes.

Table 1. Microphone Locations

Mic #	x	y	z
1	Traverse	15.13	9
2	Traverse	19.38	9
3	Traverse	23.63	9
4	Traverse	27.88	9
5	Traverse	32.13	9
6	Traverse	36.38	9
7	Traverse	40.63	9
8	Traverse	44.88	9
9	80.21	0	28.73
10	70.91	19	5.77
11	63.58	36.71	5.77
12	64.64	37.32	9.84
13	52.6	52.6	5.31
14	2	6.1	37.5
15	-24.5	-22.3	15.31
16	-11.1	-26	15.31

* All dimensions in feet, origin at rotor hub except z-dimension is height from floor.

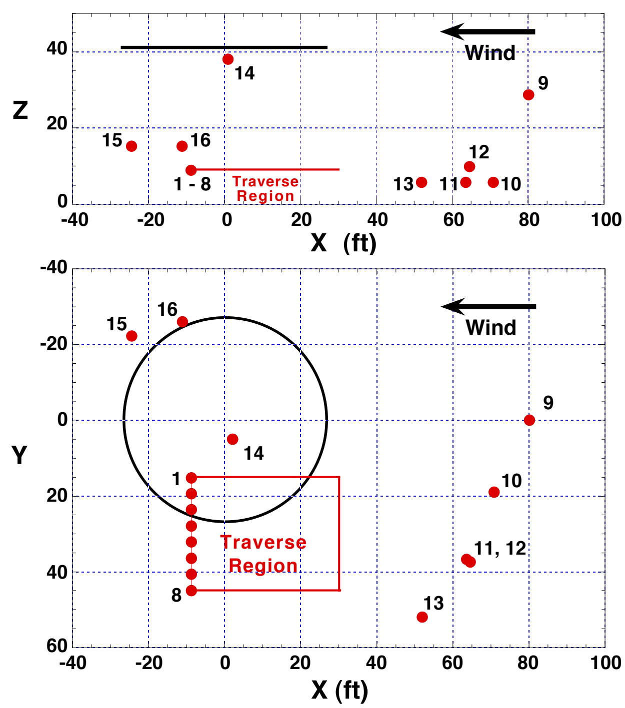

Fig. 4. Orientation of microphones and rotor in 80- by 120-Foot Wind Tunnel test section.

Table 2. Rotor Blade Strain Gage Locations

Measurement	Radial Station (% r/R)								
Flap bending	10	20	30	40	50	60	70	80	90
Lag bending	10	20	30	40	50	60	70	80	
Torsion			30		50		70		90

IBC Blade Pitch Measurements

The changes in the root blade pitch angles made by IBC excitation were measured in two ways. First, the IBC actuator displacements were measured using two LVDT transducers per actuator. Second, the total blade root pitch, flap, and lead-lag angles were measured using a device that spanned the rotor elastomeric bearing as described in Ref. 17.

The pitch angle changes at the 70% and 90% radial stations were derived using two accelerometers to sense flap acceleration before and after the pitch change axis at each station. These inputs were used to compute the outboard IBC pitch changes using the method outlined in Ref. 18.

IBC Inputs Tested

In order to test as many IBC inputs as possible in a short amount of time, only two primary wind tunnel test conditions were selected. The first test condition simulated 1-g lift (16,800 lb; C_L/σ = 0.0725) at an airspeed producing significant transition vibration (46 kts, μ = 0.1). The second test condition simulated a high BVI noise condition by tilting the rotor shaft angle aft (at 75 kts, μ = 0.175). These two test conditions are referred to as the Vibration and BVI Noise test conditions in Table 3.

For the Vibration test condition, the rotor lift, hub moment, and propulsive force were kept constant with and without IBC input. The trim was adjusted by varying the shaft angle, collective pitch angle, and lateral-longitudinal cyclic pitch angles. For the most part, the data at this condition were acquired at -0.69° and –3.0° shaft angles (forward tilt). However, some IBC inputs (most notably 2/rev IBC) required the shaft angle to be re-adjusted up to ±0.5° to match the baseline trim state. The rotor speed was maintained constant at 258 RPM for the Vibration test condition.

For the BVI Noise condition, the shaft angle was not adjusted, but rather held fixed at one of two, aft-tilted, shaft angles (4.0° and 7.0°). The collective and cyclic controls were used to maintain constant thrust coefficient and minimum 1/rev blade root flapping angle. At 75 kts airspeed, a C_T/σ = 0.09 (20,600 lbs thrust) produced an approximately 1-g lift force. The rotor control console displayed the 1/rev flapping angle so that it could be manually minimized by the rotor operator to less than ±0.2° in most cases. The RPM was adjusted to maintain a constant tip Mach number of 0.65.

Table 3 lists the IBC inputs harmonics and maximum amplitudes tested at the Vibration and the BVI Noise test conditions. In total, 253 IBC data points were acquired in 23 hours of wind tunnel test time. Most of the data were acquired with the IBC inputs held at constant amplitude while varying the phase of the IBC input. Amplitude variation was done at a few phase angles for each IBC harmonic at each test condition.

The data were acquired with mechanical motion stops set in the IBC actuators to limit the IBC maximum amplitude, first to ±1.5°, and then to ±3.5° later in the test. These precautions were taken to insure control system stability during the IBC envelope expansion. After the ±1.5° limits were replaced by the ±3.5° limits, there was only enough time remaining to test 3.0° of 2/rev IBC at the acoustic test condition and two multi-harmonic inputs at the vibration test condition. The multi-harmonic combinations were determined from an optimization program written by ZFL that estimated the optimal amplitude and phase of specified harmonic combinations using the single-frequency input vibration data.

Table 3. IBC Inputs and Test Conditions

Test Condition	Shaft Angles	IBC Harmonics and Max. Amp.	
Vibration	-3.0°	2/rev to ±1.0°	*
(C_L/σ = 0.0725;	-0.69°, -3.0°	3/rev to ±1.0°	*
Constant Hub	-0.69°, -3.0°	4/rev to ±1.0°	*
Moment &	-3.0°	5/rev to ±0.25°	
Propulsive	-3.0°	6/rev to ±0.75°	
Force at	-3.0°	7/rev to ±0.25°	
46 kts)	-0.69°, -3.0°	2/rev + 3/rev	*
	-0.69°, -3.0°	3/rev + 4/rev	*
BVI Noise	4.0°, 7.0°	2/rev to ±3.0°	
(C_T/σ = 0.09;	7.0°	3/rev to ±0.5°	
Minimum	7.0°	4/rev to ±0.5°	
Flapping &	7.0°	5/rev to ±0.5°	
M_{Tip} = 0.65 at	7.0°	6/rev to ±0.5°	
75 kts)	4.0°	2/rev + 5/rev	

* Shaft angles adjusted up to ±0.5° to maintain rotor trim.

The IBC inputs were defined by the expression

$$\theta_i = \sum_{n=2}^{7} A_n Cos\left[n\left(\Psi_1 - (i-1)(90\ \deg)\right) - \phi_n\right]$$

where θ_i is the pitch of the i^{th} rotor blade, A_n is the amplitude of the n^{th} IBC harmonic, Ψ_1 is the rotor azimuth angle of blade No. 1 (measured counter-clockwise from 0° aft), and ϕ_n is the phase angle of the n^{th} IBC harmonic.

Discussion of the Test Results

Effect of IBC on Vibration

The rotor hub forces and moments measured by the LRTA rotor balance were used to assess the level of vibration. As shown by Fig. 5, the rotor hub vibratory loads were dominated by the fourth harmonic at 46 kts, as would be expected for a 4-bladed rotor in forward flight. Some 1/rev and 8/rev hub vibration components are also present. No mobility matrix was used to dynamically amplify the 4/rev hub forces (lbs) and moments (ft-lbs) derived from the balance data.

If the following vibration metric is adopted,

$$Total_{4P} = Lift_{4P} + S_{4P} + M_{4P} + Torque_{4P}$$

where

$$S_{4P} = \sqrt{\left(Axial\ Force_{4P}\right)^2 + \left(Side\ Force_{4P}\right)^2}$$

$$M_{4P} = \sqrt{\left(Pitch\ Mom_{4P}\right)^2 + \left(Roll\ Mom_{4P}\right)^2}$$

then the effect of IBC harmonics 2/rev – 7/rev on the total 4/rev hub vibration can be shown as in Fig. 6.

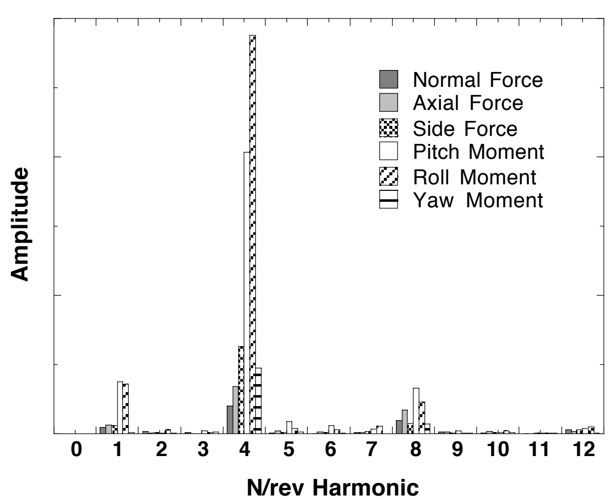

Fig. 5. Vibration spectrum at 46 kts.

The symbols denote the actual measured data, while the lines through the symbols are polynomial curve fits. In this figure, the percentage of change in vibration from the baseline level is shown as a function of the IBC input phase angle. Note that 2/rev IBC was input at 1.0° amplitude, 3/rev and 4/rev IBC were input 0.5° amplitude, and 5/rev, 6/rev, and 7/rev were input at 0.25° amplitude. The best overall vibration reduction was achieved using 3/rev IBC, with 4/rev IBC being the next best.

Figures 7, 8, and 9 show the changes in the 4/rev vibration components with application of 2/rev, 3/rev and 4/rev IBC, respectively. Although the in-plane 4/rev shear force and moment are reduced and increased together as a function of phase angle, the 4/rev lift and torque are minimized at different IBC input phase angles.

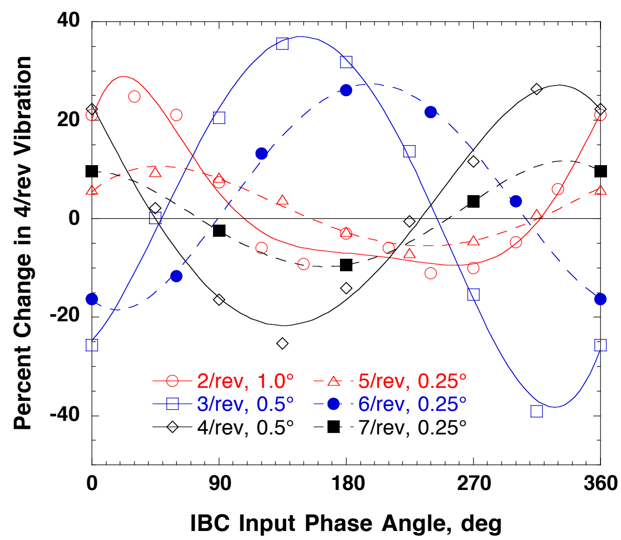

Fig. 6. Effect of IBC input on total 4/rev vibration at 46 kts (shaft angle = -3°).

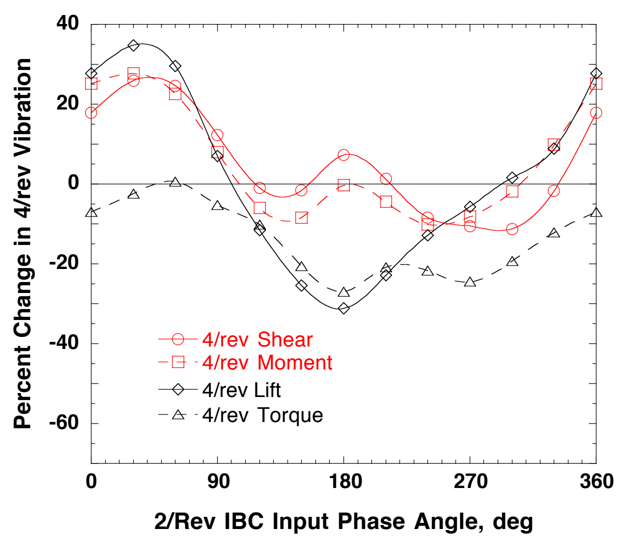

Fig. 7. Effect of 1.0° 2/rev IBC on 4/rev vibration components at 46 kts (shaft angle = -3°).

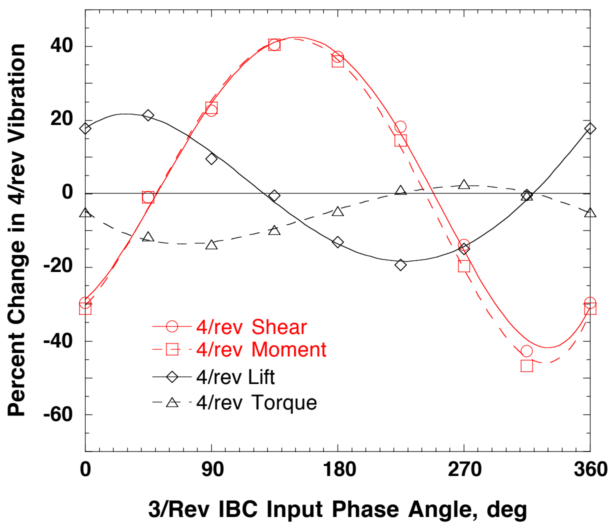

Fig. 8. Effect of 0.5° 3/rev IBC on 4/rev vibration components at 46 kts (shaft angle = -3°).

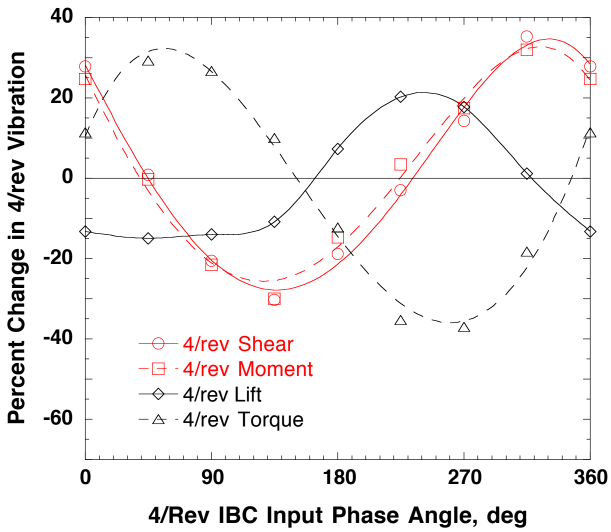

Fig. 9. Effect of 0.5° 4/rev IBC on 4/rev vibration components at 46 kts (shaft angle = -3°).

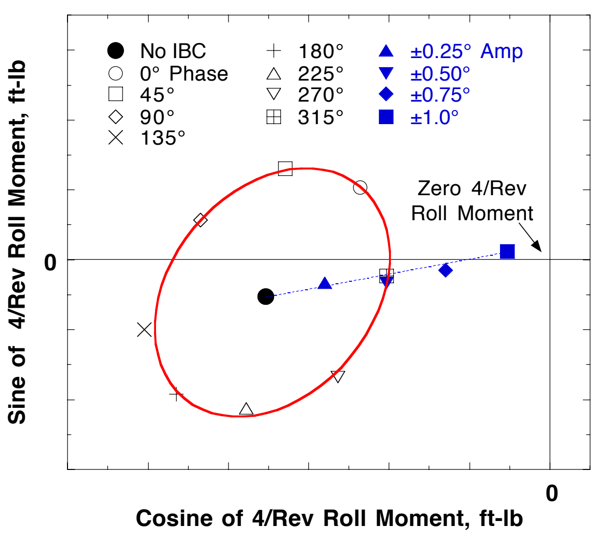

Fig. 10. Polar plot of 4/rev roll moment vibration components with 0.5° 3/rev IBC at 46 kts.

Figure 10 presents a plot of the sine coefficient of 4/rev roll moment versus the cosine coefficient of 4/rev roll moment for the phase sweep of 3/rev IBC at 0.5° amplitude. The data form an ellipse about the baseline vibration (no IBC) point. The plot also shows the roll moment data obtained from an amplitude sweep at the 315° phase angle. Since the distance from the baseline point is proportional to the IBC amplitude, the system is clearly linear with respect to roll moment and 3/rev IBC input. The zero vibration origin is not quite reached, but appears as though it could be given a little higher amplitude and a slightly different phase angle. Five other polar plots would be needed to show the other five rotor balance forces and moments.

Figure 11 shows that the total 4/rev vibration was reduced up to 70% with 1.0° of 3/rev input at the 315° phase angle. From 0° to 0.75°, the vibration reduction is linear with the 3/rev input amplitude. However, from 0.75° to 1.0°, the rate of reduction decreases. In terms of what happened to the individual components, Fig. 12 shows that although the 4/rev in-plane hub shears and moments were reduced slightly over 80% for the 1.0° input, the 4/rev lift and torque were generally not affected. Figure 13 shows that the vibration was not increased at other frequencies with the application of 1.0° 3/rev IBC at the 315° phase angle.

The vibration data obtained for the single-frequency inputs were used in a regression analysis to see if combinations of the IBC harmonics could produce better vibration suppression. Unfortunately, only a few combinations could be tested. The best one of these inputs was a combination of 3/rev IBC at 1.23° amplitude and 322° phase with 4/rev IBC at 0.84° amplitude and 303° phase. The resulting vibration reductions are shown in Table 4. Although

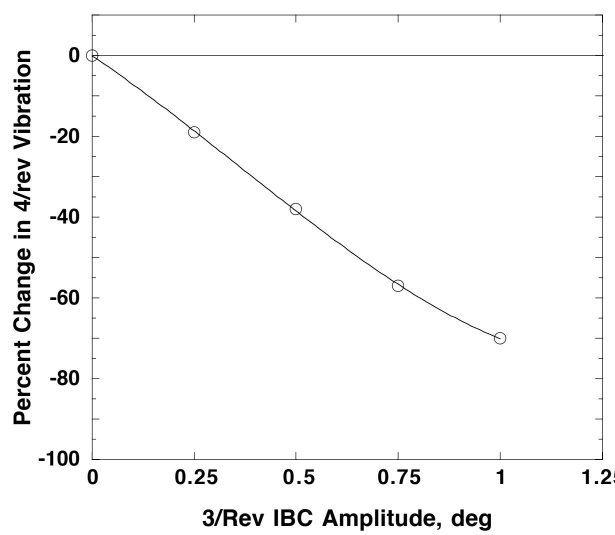

Fig. 11. Effect of 3/rev IBC at 315° phase angle on the total 4/rev vibration at 46 kts.

the multi-harmonic input reduced the total 4/rev vibration index less than the 3/rev IBC did acting alone (64% versus 70%), the 3+4/rev input did reduce all of the 4/rev vibration components. Overall, 3/rev IBC did better because the 4/rev hub shear and moment reductions were relatively large compared to the 4/rev lift force and torque.

Table 4. Percent Change in 4/rev Vibration

IBC Input	Lift	Shr	Mom	Torq	$Total_{4P}$
3P*	-4	-80	-82	+1	-70
3P + 4P**	-20	-67	-69	-38	-64

* 1.0° 3/rev at 315° phase
** 1.23° 3/rev at 322° + 0.84° 4/rev at 303°

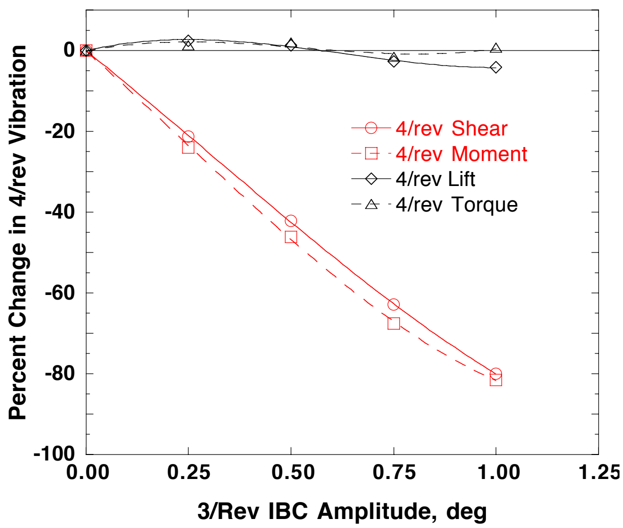

Fig. 12. Effect of 3/rev IBC at 315° phase angle on the 4/rev vibration components at 46 kts.

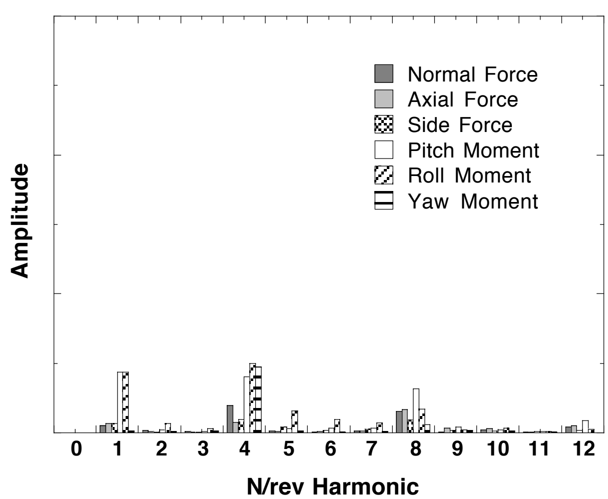

Fig. 13. Vibration spectrum with 1.0° of 3/rev IBC applied at 315° phase angle. (46 kts, baseline levels shown in Fig. 5.)

Effect of IBC on BVI Noise

Acoustic data were acquired to evaluate the effects of IBC on blade vortex interaction (BVI) noise. These measurements were made using both fixed-position and movable microphones. A traverse system was used to move an array of eight microphones below the rotor on the advancing side. Eight fixed-position microphones were located on the retreating side and in front of the rotor (as previously shown in Fig. 4).

Analog filters with an upper cut-off frequency of 1670 Hz were used to avoid aliasing of the microphone data. To extract the BVI noise component, the microphone data were digitally band-pass filtered (post-process) between 172 Hz and 860 Hz (40/rev – 200/rev frequencies). Frequencies above 860 Hz were eliminated in order to reduce extraneous high-frequency content. Eliminating the frequencies below 172 Hz reduced the tunnel background noise contamination and removed the blade loading noise component. The resulting BVI noise metric is the band-limited, sound pressure level (BL-SPL). The unfiltered data are retained in the data base.

To simulate a condition having high BVI noise, the rotor shaft angle was tilted aft. Most of the IBC inputs were introduced at an airspeed of 75 kts and a shaft angle of 7°. Ideally, an airspeed near 100 kts would have been desired to more closely simulate the maximum BVI levels sometimes encountered in descent flight, but that speed was beyond the facility limits (85 kts). The 2/rev IBC inputs were also repeated at a 4° shaft angle. For both cases, a tip Mach number of 0.65 and C_T/σ = 0.09 were maintained. The microphone traverse was moved to obtain data at the better IBC inputs; otherwise, it was parked at a position 5.83 ft forward of the hub center (station 70).

Figure 14 shows the changes in the BL-SPL BVI noise metric for microphone 3 with the traverse parked at station 70 and the rotor shaft angle at 7°. It is evident that at this condition all of the IBC harmonics reduce advancing side BVI noise if introduced at the appropriate phase angle. However, for these same test points, Fig. 15 shows that only the 2/rev and 6/rev IBC harmonics produce substantial BVI noise reductions on the retreating side of the rotor.

Figure 16 shows the effect of 2/rev IBC on advancing-side microphones when introduced at several amplitudes. These data were acquired with the traverse parked at station 70, the rotor shaft angle at 4°, and the IBC input phase angle set at

180°. As the IBC amplitude is increased to 3°, some microphones show a noise decrease on the order of 12 dB.

On the retreating side of the rotor, data taken from microphones 15 and 16 for these same inputs show that the BVI noise is also decreased for the 2/rev IBC introduced at 180° phase angle (Fig. 17). Interestingly, whereas the advancing side BVI noise reduction is fairly monotonic with amplitude, the retreating side BVI noise is first rapidly decreased with small amplitude, then increased at higher amplitudes, before finally being further decreased. At the 3° amplitude level, the BL-SPL noise of these microphones is reduced on the order of 10 dB. However, this should not be construed to mean that the noise was reduced to this level for most of the area on the retreating side, since the microphones were not far apart.

A traverse sweep was not performed for exactly this input, but rather for 2/rev input at 3° amplitude and 190° phase angle. The data for this sweep of the traverse are shown in Fig. 18. This 2/rev input is shown to decrease the advancing side BVI noise about 6 to 8 dB (50 to 60%) in most locations of the traversed region.

Although the 2/rev IBC input showed large noise reductions, these inputs also nearly doubled the 4/rev in-plane shear and hub moment vibrations. Figure 19 shows the effect of 1.5° 2/rev IBC with the rotor shaft angle at 4.0°. Figure 20 shows the changes in the 4/rev vibration components as the 2/rev amplitude is increased at the 180° phase angle that decreased the BVI noise. Previous IBC and HHC testing with the BO-105 rotor, however, indicates that this increased vibration should be expected, as explained in the next section.

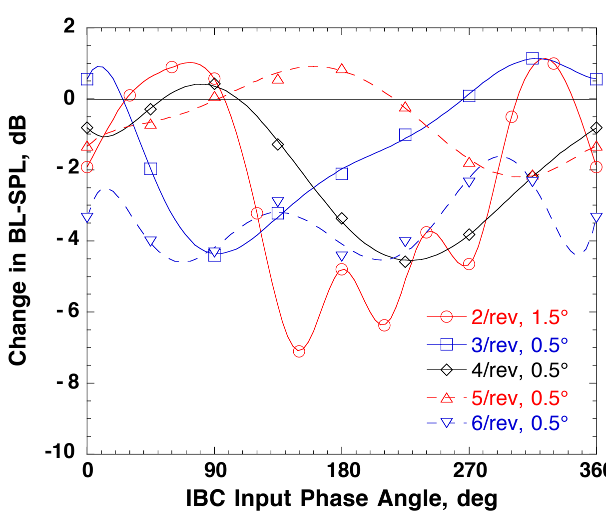

Fig. 14. Changes in advancing side BVI noise measured by microphone 3 (at sta. 70) for 2/rev-6/rev IBC input at 75 kts (shaft angle = 7°).

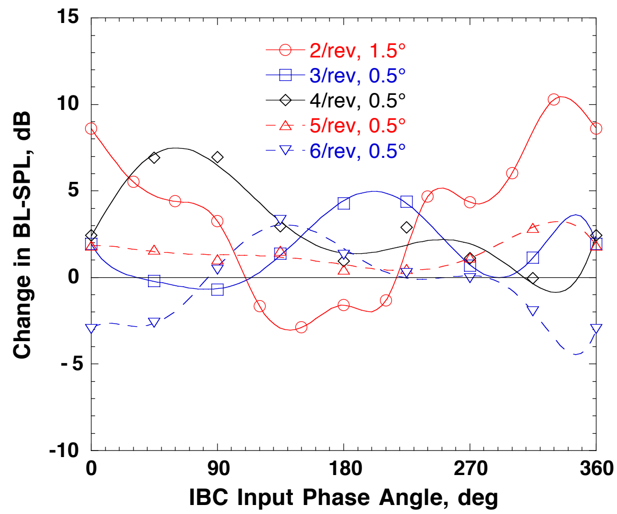

Fig. 15. Changes in retreating side BVI noise measured by mic 16 for 2/rev-6/rev IBC input at 75 kts (shaft angle = 7°).

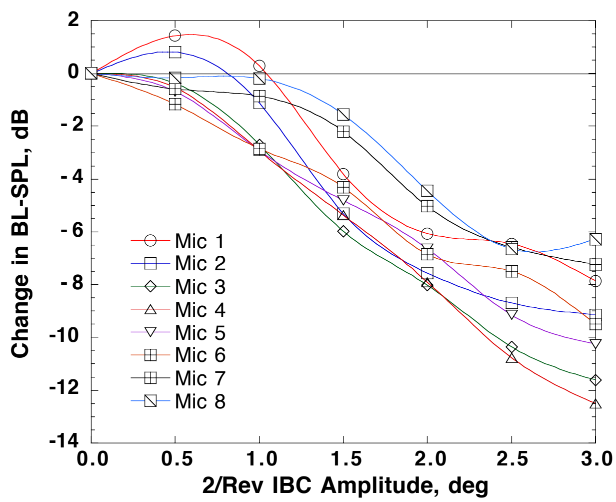

Fig. 16. Changes in advancing side BVI noise at 75 kts with 2/rev IBC at 180° phase angle (traverse parked 5.83 ft forward of hub center; shaft angle = 4°).

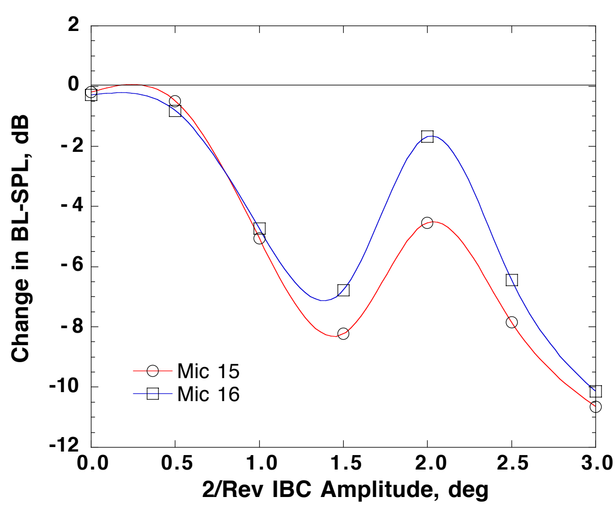

Fig. 17. Changes in retreating side BVI noise at 75 kts with 2/rev IBC at 180° phase angle (shaft angle = 4°).

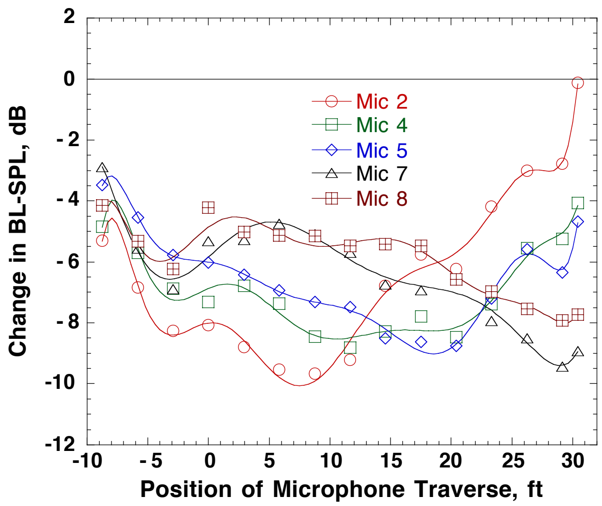

Fig. 18. Changes in advancing side BVI noise with 3° of 2/rev IBC at 190° phase angle for traverse sweep at 75 kts (shaft angle = 4°).

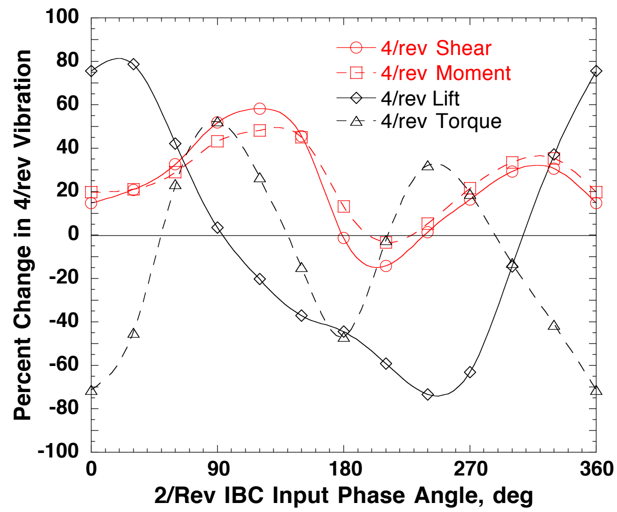

Fig. 19. Changes in 4/rev vibration with 1.5° 2/rev IBC at 75 kts (shaft angle = 4°).

Comparison to the BO-105 IBC Data

Six years prior to this wind tunnel test, a similar IBC system was tested in the NASA Ames 40- by 80-Foot Wind Tunnel on a BO-105 rotor (Refs. 13-15, and 18). Whereas the UH-60A is an articulated rotor of 26.833 ft radius, the BO-105 is a hingeless rotor having a smaller radius of 16.11 ft. Although different in design, the preliminary data gathered for the UH-60A rotor indicate a certain similarity with respect to BVI noise and vibration reduction.

Similar to the UH-60, 2/rev IBC was the only IBC harmonic that simultaneously reduced BVI noise on both sides of the BO-105 rotor. Figure 21 shows the BO-105 advancing-side and retreating-side noise metrics formed from four microphones on the advancing side of the rotor and three from the retreating side.

However, for this same IBC input, the 4/rev vibration levels were also much increased over the baseline values, just like the UH-60. The 4/rev vibration components for the BO-105 rotor are shown in Fig. 22. Similar to the UH-60, the BO-105 4/rev hub moment and 4/rev in-plane shear force closely track each other, while the 4/rev lift and torque vibration are minimized and maximized at different 2/rev input phase angles.

Fortunately, as shown in Refs. 15, 18, and 19, by using a combination of IBC harmonics, the BO-105 BVI noise and 4/rev vibration levels could be simultaneously reduced by 85%. It is hoped that such multi-harmonic combinations can also be demonstrated to simultaneously reduce UH-60 noise and vibration to the same extent in future wind tunnel testing.

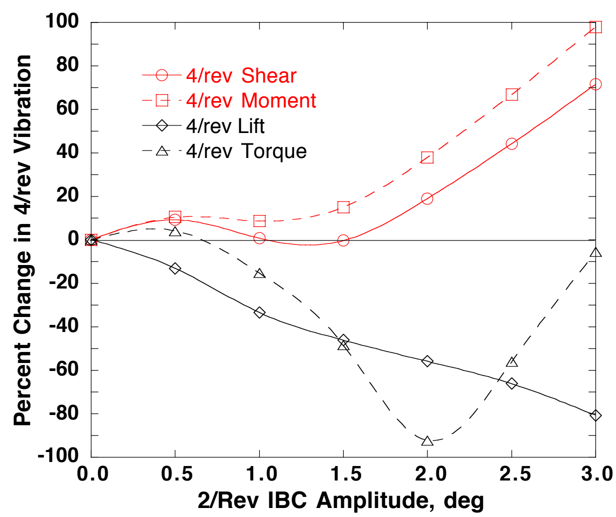

Fig. 20. Changes in 4/rev vibration at 75 kts with 2/rev IBC at 180° phase angle (shaft angle = 4°).

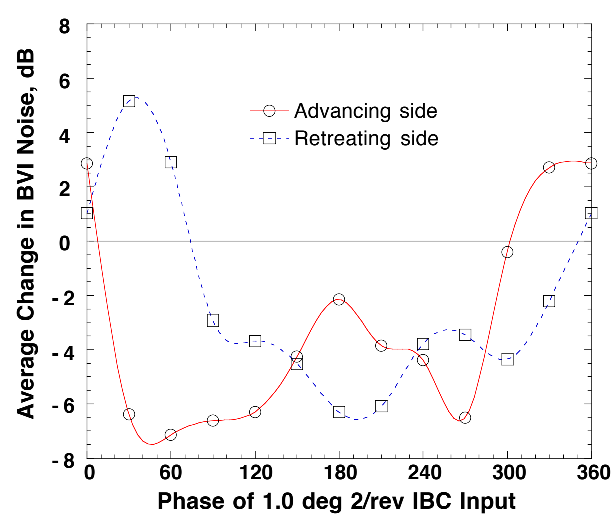

Fig. 21. BO-105 BVI noise reduction measured in Ames 40- by 80-Foot Wind Tunnel using 1.0° 2/rev IBC at 65 kts (shaft angle = 4°), [Ref. 18].

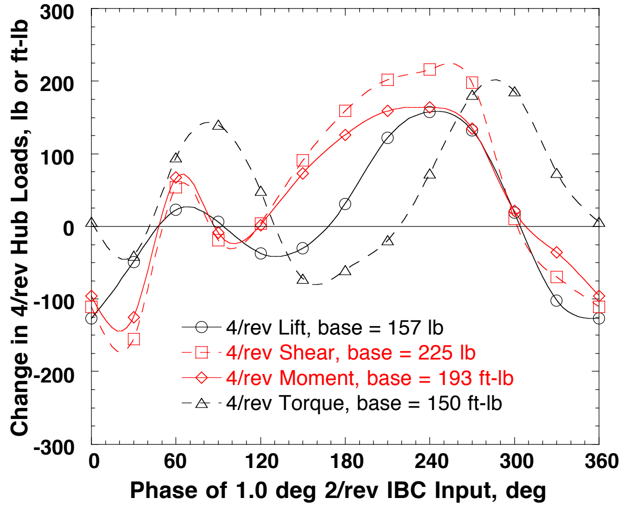

Fig 22: BO-105 4/rev vibration levels measured in Ames 40- by 80-Foot Wind Tunnel at 65 kts using 1.0° 2/rev IBC (shaft angle = 4°), [Ref. 18].

Concluding Remarks

A test of a full-scale, UH-60 IBC system was conducted in the NASA Ames Research Center 80- by 120-Foot Wind Tunnel. Although this test was intended to be mainly a check-out test of the ZFL IBC system, the hardware was made operational, thereby allowing the acquisition of data to document the effects of open-loop, single-harmonic IBC on UH-60 noise and vibration.

The acquired IBC data include rotor performance data, hub force and moment vibration data, acoustic data, rotor load data, control system load data, and control system motion data. Only the noise and vibration data were discussed in this paper.

The data indicate that 3/rev IBC is the best single-frequency input for UH-60 vibration reduction at low-speed, forward flight conditions. This harmonic was shown to eliminate more than 70% of the total 4/rev hub vibration. The vibration was also strongly effected by 4/rev IBC as well.

Large BVI noise reductions were produced using 2/rev IBC at test conditions simulating descent flight. The BVI noise was reduced over 12 dB (75%) at some locations and the average BVI noise reduction was on the order of 6-8 dB. However, the large noise reductions were also accompanied by a large increase in the 4/rev hub shear and moment vibrations. These results are comparable to the IBC results obtained from previous testing with a BO-105 rotor.

Testing of the UH-60A and growth rotors in the Ames 40- by 80-Foot Wind Tunnel is planned to evaluate the ability of multi-harmonic IBC to simultaneously eliminate UH-60 BVI noise and vibration. This testing will also serve to establish the effect of IBC on high-speed rotor performance.

Acknowledgements

The authors gratefully acknowledge that this research milestone would not have been achieved without the efforts of many talented people at NASA, AFDD, ZFL, and Sikorsky. On the NASA/AFDD side, thanks are given to Al Lizak (Test Manager), Mark McGlaughlin (Deputy Test Manager), Alex Sheikman (Instrumentation Engineer), Leon Quintela (Instrumentation), Lanah Hoang (Data System), Martha Peterson (Software Engineer) and Dr. William Warmbrodt (Chief of Aeromechanics Branch), for their tireless support of this project. On the ZFL side, deep appreciation is noted for Hans-Juergen Goette (Designer), Karl-Heinz Bock (Controls Lead), Jens Scharre (IBC Operator), and Uwe T.P. Arnold (Director R&D). On the Sikorsky side, the planning and support efforts over several years by Ed Beno (Rotor Design), Andy Bernhard (Dynamics), Len Doolin (Rotor Design), Jamie Duncan (Test), Rance Fox (Rotor Design), Bob Holt (Test), Tom Lawrence (Handling Qualities), Phil Love (Reliability), Herbie Mann (Instrumentation), Phil Perschbacher (Test), Jamie Renna (Rotor Design), Mike Torok (Aerodynamics), and Bill Welsh (Dynamics) provided valuable advice toward making this phase a success.

The ZFL portion of the research related to this report has received partial funding from the German Federal Ministry of Education and Research (BMBF) as well as the Federal Ministry of Economics and Technology (BMWi).

References

1) Norman, T.R., Shinoda, P., Kitaplioglu, C., Jacklin, S.A., and Sheikman, A., "Low-Speed Wind Tunnel Investigation of a Full-Scale UH-60 Rotor System", American Helicopter Society 58th Annual Forum, Montreal, Canada, June 2002.

2) McCloud, J.L., III, and Kretz, M., "Multicyclic Jet-Flap Control for Alleviation of Helicopter Blade Stresses and Fuselage Vibration", NASA SP-352, 1974.

3) Hammond, C.E., "Wind Tunnel Results Showing Rotor Vibratory Loads Reduction Using Higher Harmonic Blade Pitch", Journal of the American Helicopter Society, Vol. 28, No. 1, Jan. 1983.

4) Shaw, J., Albion, N., Hanker, E.J., and Teal, R.S., "Higher Harmonic Control: Wind Tunnel Demonstration of Fully Effective Vibratory Hub Force Suppression", American Helicopter Society 41st Annual Forum, Fort Worth, TX, May 1985.

5) Straub, F. and Byrns, E., "Application of Higher Harmonic Blade Feathering on the OH-6A Helicopter for Vibration Reduction," NASA CR 4031, 1986.

6) Miao, W., Kottapalli, S.B.R., and Frye, M.M., "Flight Demonstration of Higher Harmonic Control (HHC) on S-76", American Helicopter Society 42nd Annual Forum, Washington, DC, June 1986.

7) Polychroniadis, M., and Achache, M. "Higher Harmonic Control: Flight Tests of an Experimental System on SA 349 Research Gazelle", American Helicopter Society 42nd American Helicopter Society Forum, Washington, DC, June 1986.

8) Brooks, T.F., Booth, E.R. Jr., Jolly, J.R. Jr., Yeager, W.T. Jr., and Wilbur, M.L., "Reduction of Blade-Vortex Interaction Noise Using Higher Harmonic Pitch Control", NASA Technical Memorandum 101624, July, 1989.

9) Yu, Y.H., Gmelin, B., Heller, H., Philippe, J.J., Mercker, E., and Preisser, J.S., "HHC Aeroacoustics Rotor Test at the DNW - The Joint German/French/US HART Project", 12th European Rotorcraft Forum, Amsterdam, The Netherlands, October 1994.

10) Splettstoesser, W.R., Schultz, K.-J., Kube, R., Brooks, T.F., Booth Jr., E.R., Niesl, G., and Streby, O., "A Higher Harmonic Control Test in the DNW to Reduce Impulsive BVI Noise", Journal of the American Helicopter Society, Vol. 39, No. 4, October 1994.

11) Richter, P., Eisbrecher, H.-D., and Kloeppel, V., "Design and First Flight Test of Individual Blade Control Actuators", 16th European Rotorcraft Forum, Glasgow, Scotland, September 1990.

12) Teves, D., Kloeppel, V., and Richter, P., "Development of Active Control Technologies in the Rotating System, Flight Testing and Theoretical Investigations", 18th European Rotorcraft Forum, Avignon, France, September 1992.

13) Jacklin, S.A., Nguyen, K.Q., Blaas, A., and Richter, P., "Full-Scale Wind Tunnel Test of a Helicopter Individual Blade Control System", American Helicopter Society 50th Annual Forum, Washington, DC, May 1994.

14) Jacklin, S. A., Blaas, A., Teves, D., and Kube, R., "Reduction of Helicopter BVI Noise, Vibration, and Power Consumption Through Individual Blade Control", American Helicopter Society 51th Annual Forum, Fort Worth, Texas, May 1995.

15) Jacklin, S.A., Blaas, A., Swanson, S.M., and Teves, D., "Second Test of a Helicopter Individual Blade Control System in the NASA Ames 40- by 80-Foot Wind Tunnel", American Helicopter Society 2nd International Aeromechanics Specialists Conference, Bridgeport, CT, October 1995.

16) Haber, A., Jacklin, S.A., and deSimone, G., "Development, Manufacturing, and Component Testing of an Individual Blade Control System for a UH-60 Helicopter Rotor", American Helicopter Society Aerodynamics, Acoustics, and Test and Evaluation Specialists Meeting, San Francisco, CA, January 2002.

17) Kufeld, R.M., Balough, D.L, Cross, J.L., Studebaker, K.F., Jennison, C.D., and Bousman, W.G., "Flight Testing the UH-60A Airloads Aircraft", American Helicopter Society 50th Annual Forum, Washington, DC, May 1994.

18) Jacklin, S.A., Swanson, S., Blaas, A., Richter, P., Teves, D., Niesl, G., Kube, R., and Gmelin, B., "Investigation of a Helicopter Individual Blade Control (IBC) System in Two Full-Scale Wind Tunnel Tests", NASA TM to be published June 2002.

19) Mueller, M., Arnold, U.T.P., Morbitzer, D., "On the Importance and Effectiveness of 2/rev IBC for Noise, Vibration, and Pitch Link Load Reduction", 25th European Rotorcraft Forum, Rome, Italy, September 1999.